AC Loss Measurements of Superconducting Quadrupole Magnet Nb3Sn

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Abstract

Energy loss measurements were recently performed on the superconducting Quadrupole Mirror Magnet, TQM-03, at 4.2K. These studies were done at the Fermilab Vertical Magnet Test Facility (VMTF) located in Technical Division's IB1. For measuring and calculating the energy losses a PXI based data acquisition system was used, which was written in National Instruments LabView version 8.6. Several parameters were investigated in order to characterize and optimize the system performance. The dependence of energy losses verse the ramp rate, the sampling rate and the period of integration was investigated at magnet temperature 4.2 K.

Introduction

Superconducting magnets are used to bend and focus charged particle beams, for example, the protons and anti-protons in the Tevatron in the Fermilab laboratory. Due to zero resistance of these magnets current can be passed through them almost without any energy losses. But if non-constant current is applied to the superconducting magnets the energy losses are always exist. It can be magnetization (or hysteresis) loss and resistive (or eddy current) loss. The value of energy losses in the magnet is important thing because of several reasons. First of all, it is helpful for understanding how much heat should we carry off for providing the heat abstraction and also it is necessary for magnet design.

Theory

There are two types of energy losses: magnetization (or hysteresis) loss and resistive (or eddy current) loss. The first one depends on the maximum magnetic induction and is associated with the hysteresis loop. In the main case, superconducting samples can be divided into two parts: the volume part and tine surface part where image current circulate. Due to this persistent current the values of the inner and the outer magnetic field are not the same, which is the reason for the existence of a hysteresis loop. The second type of energy losses is the resistive loss. Technically, superconductors must be stabilized by incorporating into the wires and composites a matrix of high electric and thermal conductivity such as Cu or Al. In time-varying magnetic fields eddy currents will be induced in these resistive matrices. In contrast to the hysteresis loss in the superconductor, which only depends on the maximum magnetic induction, the eddy current losses are frequency dependent. And therefore, the value of resistive loss is equal to zero when the ramp rate is zero.

For measuring alternating current (AC) losses two methods are commonly used: calorimetric and electrical. In the calorimetric method the volume of gas which is boiled away by the AC loss power is measured. The electrical method of loss measurement works by measuring the net power supplied to the coil. It is faster and more versatile than the calorimetric method. The basic idea of this method is to multiply current by voltage and then to integrate the product electronically over one cycle. The electrical method is best suited to the measurement of total loss in an isolated coil powered by an AC. In this case it will give accurate results. If the coil is also subjected to fluctuating fields coming from an external source this method will ignore some of the losses arising from work done by these fields [1].

In the experiment Nb3Sn superconducting quadrupole magnet was used. Fig. 1 illustrates the properties of Nb3Sn. Also it shows the jc – Tc – Bc diagram of NbTi for comparison. To describe these properties fully, it is necessary to insert terms of critical current density (jc), critical temperature (Tc) and critical field (Bc). It can be seen from this figure these values are bigger for Nb3Sn. All of these properties are related to each other by the critical surface in BJT space where superconductivity prevails below this surface and normal resistivity above it.

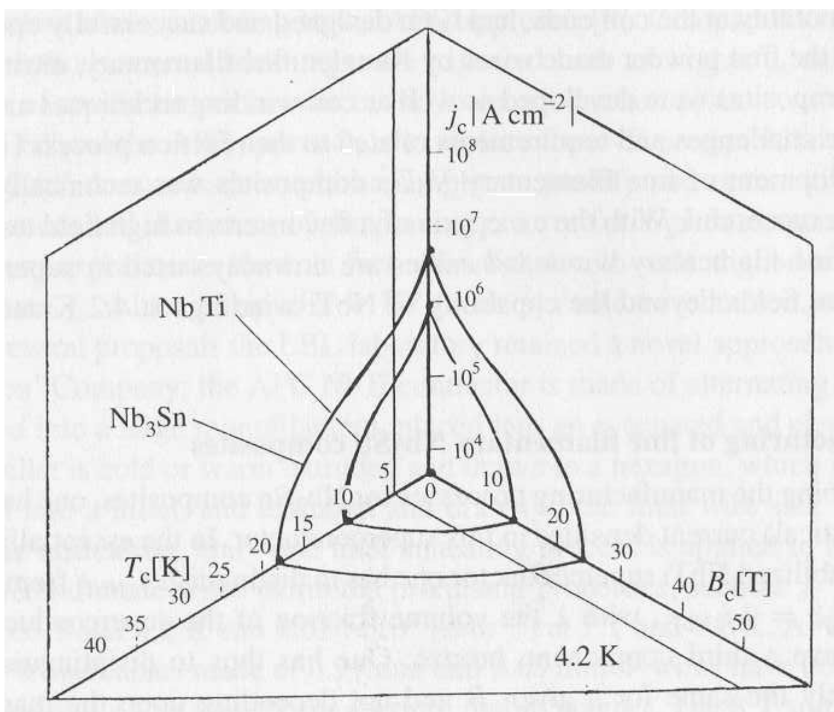

Fig. 1. The jc – Tc – Bc diagram of Nb3Sn and NbTi [2].

In order to support the necessary temperature level (in our case T ~ 4.2 K) we should constantly cool the magnet because in real experiment energy losses always exist. But we have to know the value of energy losses in the magnet for understanding how much heat should we carry off.

Experimental setup

The schematic of the electrical superconducting (SC) magnet energy loss measurement system is presented in the fig.2. A 16-Bit High-Speed Analog Output (DAC 6733) was used for generation a signal with a range of ±10 V. Maximum level of current was 30 000 A (transmission function for HOLEC is 3000 A/V). In experiments for measuring AC energy losses a SC magnet was implemented and we pass excite the magnet with a triangle source with the amplitude of several thousands of amperes (6 500 A). For measuring the voltage and the current 7 ½ - digit flex millimeters (DMM 4071) are used.

For doing the calibration process the resistive load was used instead of the real magnet and the amplitude of signal was varied from 0 to 12 A. The schematic is shown in fig. 3. The current through the shunt and the voltage on the load were measured.

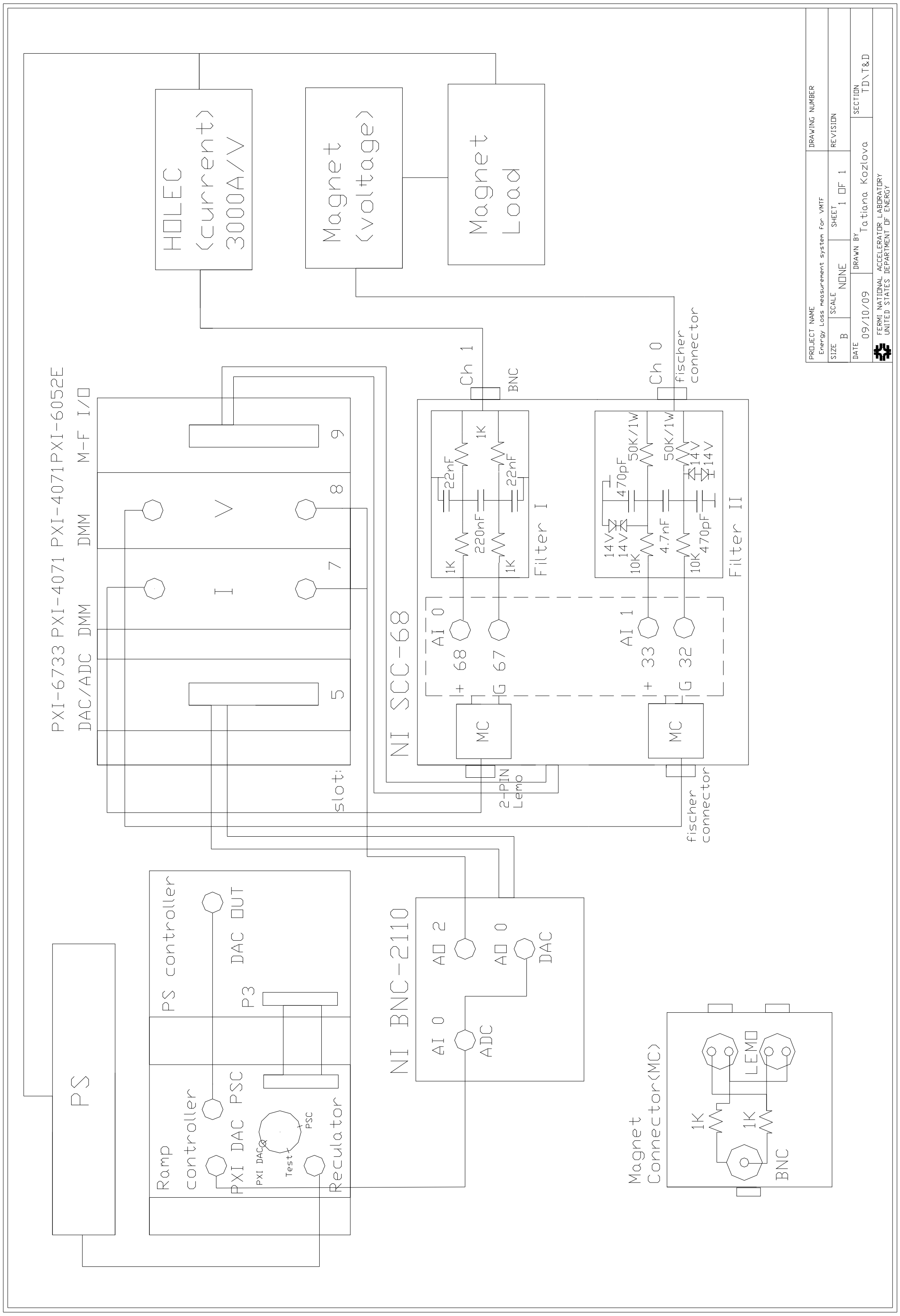

Fig. 2. Energy loss measurement system for Vertical Magnet Test Facility (VMTF)

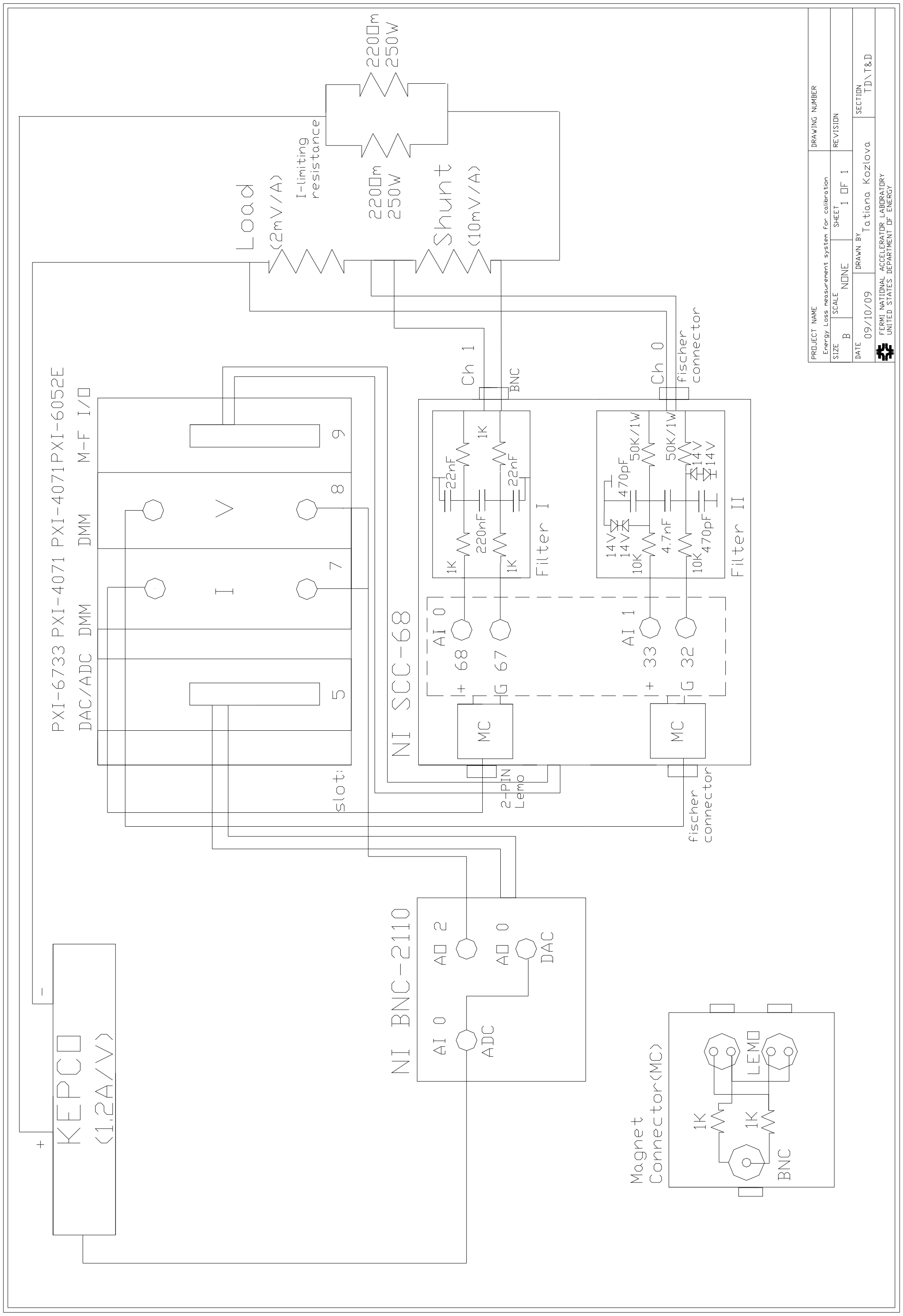

Fig. 3. Energy loss measurement system for calibration

The energy loss program was written in National Instruments LabView version 8.6. The front panel of this program is presented in fig. 4. The user can setup test parameters such as the ramp rate of a signal, the number of cycles, profiles and ramps, the time dwell, the range of applied current and the level of the noise. After calculations the value of energy loss per cycle and the mean root square deviation will be received. Profiles of the waveform signal, of the current through the chain and the load voltage will be presented in plots. Also it shows the energy verse ramp rate dependence. An example of the energy loss code, eieo (for energy in – energy out), is presented in fig. 5. It demonstrates the small part of the whole code associated with loading a waveform ramp profile.

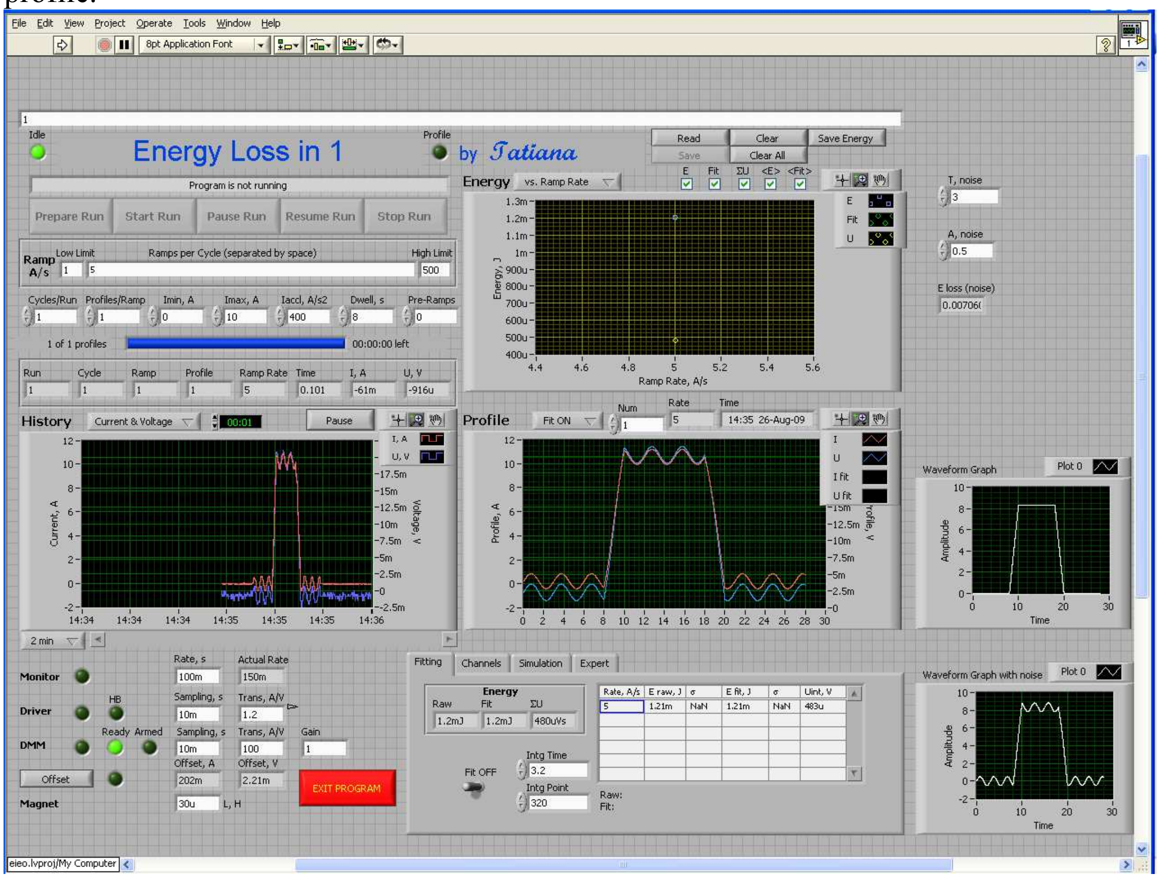

Fig. 4. The front panel of the “eieo” program for energy loss calculation

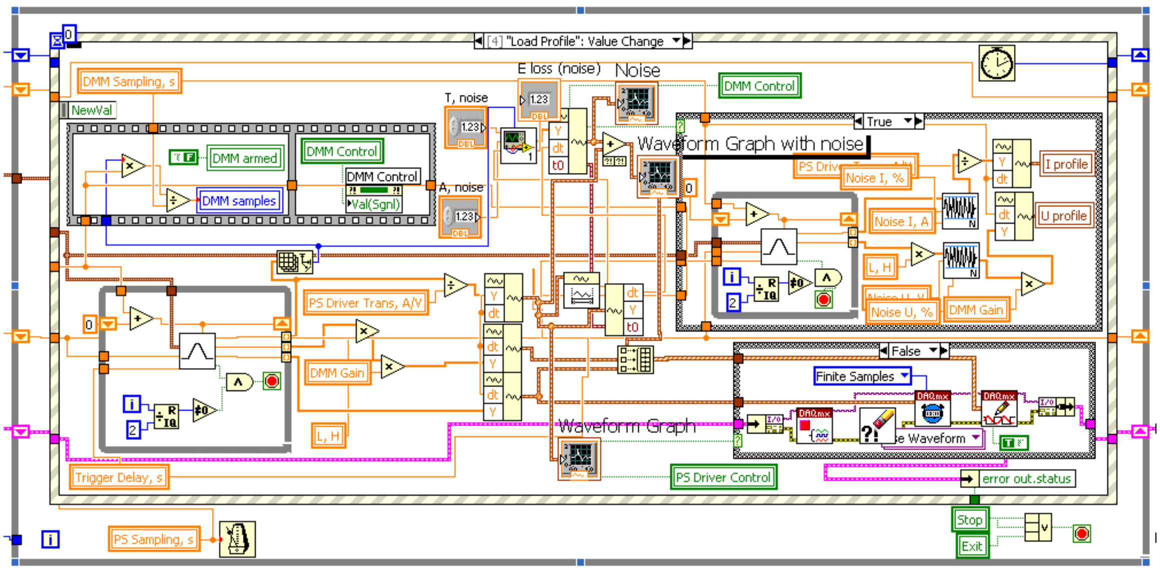

Fig. 5. The fragment of the block diagram of "eieo" program for energy loss calculation

The "eieo" program collects raw data from the DMMs, calculates the energy loss, and writes the results to a ".txt" file. By formula (1) the value of energy loss in the SC magnet can be calculated by integrating the power during the ramp cycle

$$W = \int U \cdot I \cdot dt \qquad (1)$$

where U is the magnet voltage and I is the current through the chain.

Thus using different values for the ramp rate the measurements of AC losses as a function of ramp rate were performed. After the linear fitting to the ramp rate data corresponding to the AC loss hysteresis losses were determined (while the offset term or where the ramp rate is equal to 0). The eddy current losses are determined by the slope of the loss/cycle vs. ramp rate data for ramp rates ≤75 A/sec [[3]].

Results and discussion

1) Calibration of Lab View program for energy loss measurements without noise

For performing a calibration of the "eieo" program (the schematic is presented in fig. 3) a precision load resistance is used in place of the SC magnet (transfer function is 10 A/20 mV) and ramped to low current via the DAC signal generator. The typical profile of signal is presented in fig. 6.

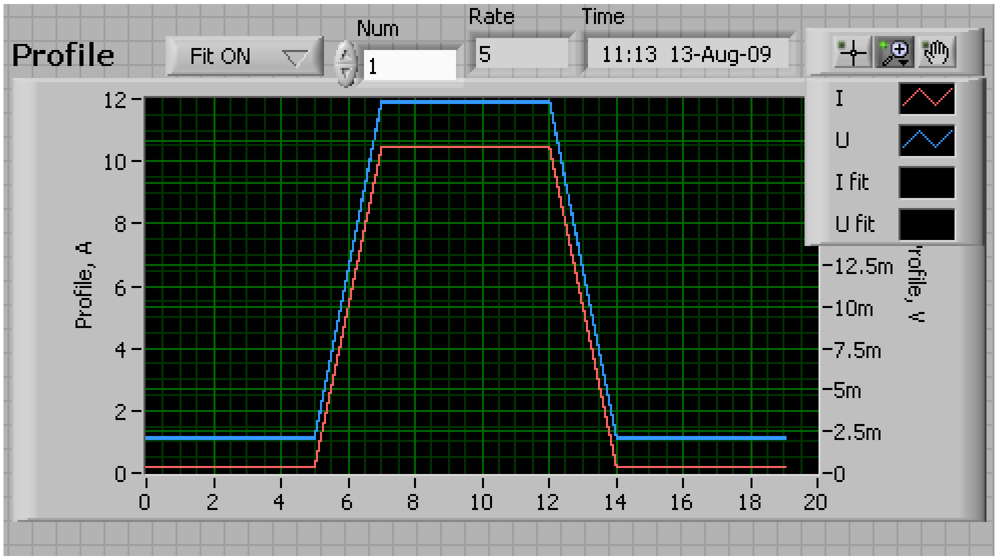

Fig. 6. Profile of signal (ramp rate 5A/s)

Results of AC energy loss measurements are presented in fig. 7. Where
W1 - energy losses calculating using the program “eieo”,
W2 - energy losses calculating using the program Excel by the formula (2)

$$W2 = (\sum_{i=1}^{N} I_i \cdot U_i) \cdot \frac{t}{N} \tag{2}$$

where t – the time of the signal, N – number of points,
W3 - energy losses calculating using the program Excel by the formula (3)

$$W3 = R \cdot \sum_{i=1}^{N} I_i^2 \cdot \frac{t}{N} \tag{3}$$

where R=2mΩ – the resistance of the load.

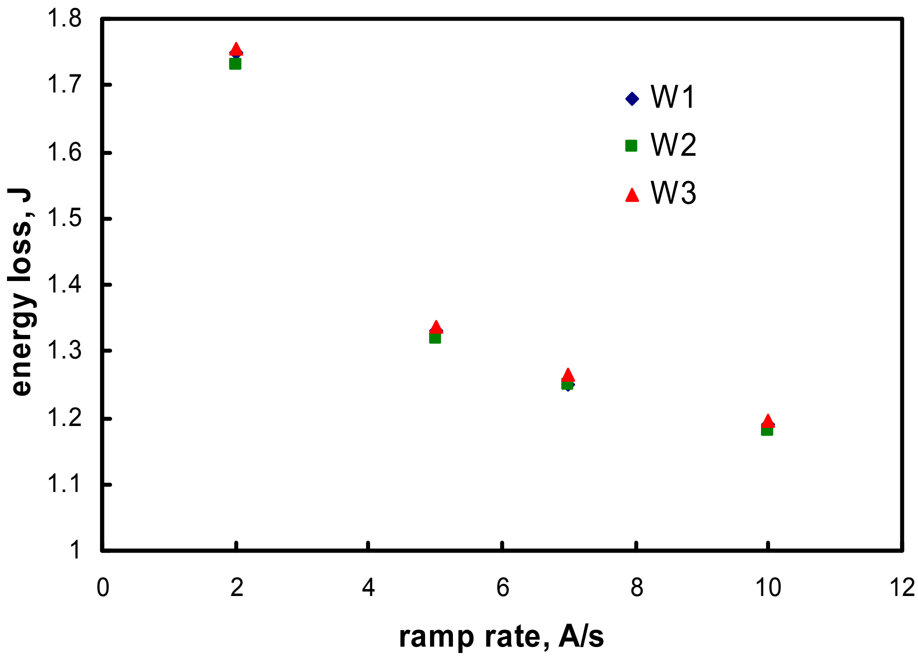

Fig. 7. AC losses as a function of ramp rate

This figure shows a good correlation between theoretical predictions (W3) and experimental results (W1). Thus the precision of measuring energy losses using the “eieo” program is about 1%.

Also the series of experiments were performed for understanding the necessary number of ramp profiles for correct statistics. Results are presented in fig. 8.

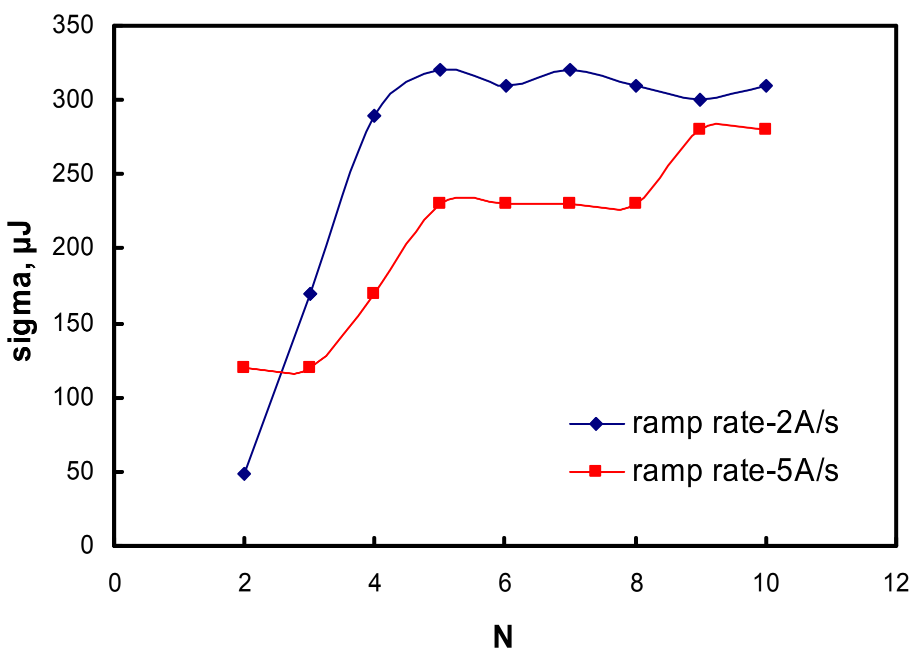

Fig. 8. Mean root square deviation as a function of number of ramp profiles

Using the calculated data as the base the minimum number of ramp profiles is equal to 5 because in excess of this value the mean root square deviation (sigma) is almost constant.

2) Calibration of Lab View program for energy loss measurements with noise

In these experiments the noise was added as an additional sinusoidal signal to the generator. The typical profile of signal is presented in fig. 9.

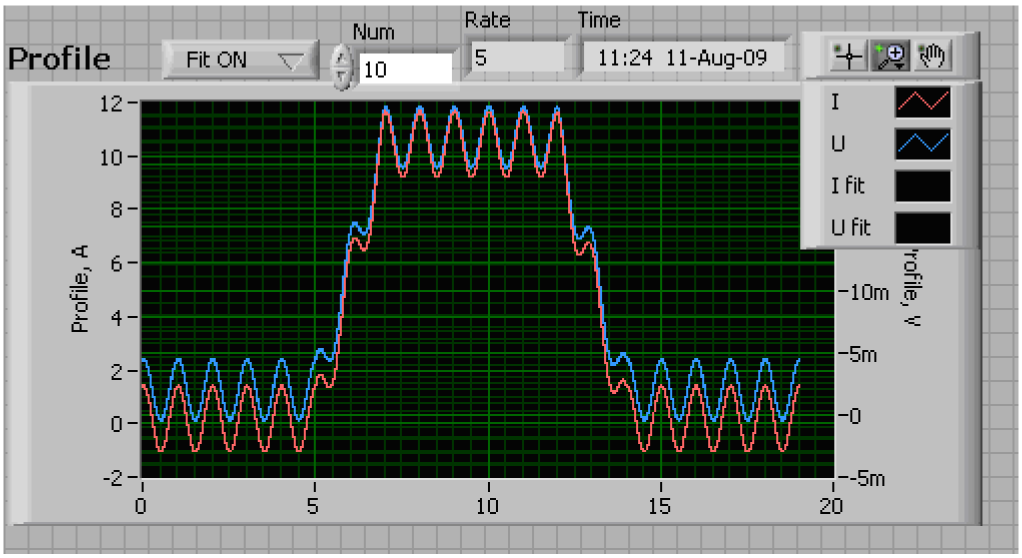

Fig. 9. Profile of signal (ramp rate 5A/s) with noise (amplitude 1 A, period 1s)

Results of AC energy loss measurements with noise are presented in fig. 10. Where
W1 - energy losses calculating using the program “eieo”,
W3 - energy losses calculating using the program Excel by the formula (3).

This figure shows a correlation between theoretical predictions (W3) and experimental results (W1). Thus the precision of measuring energy losses using the “eieo” program with noise is about 10%.

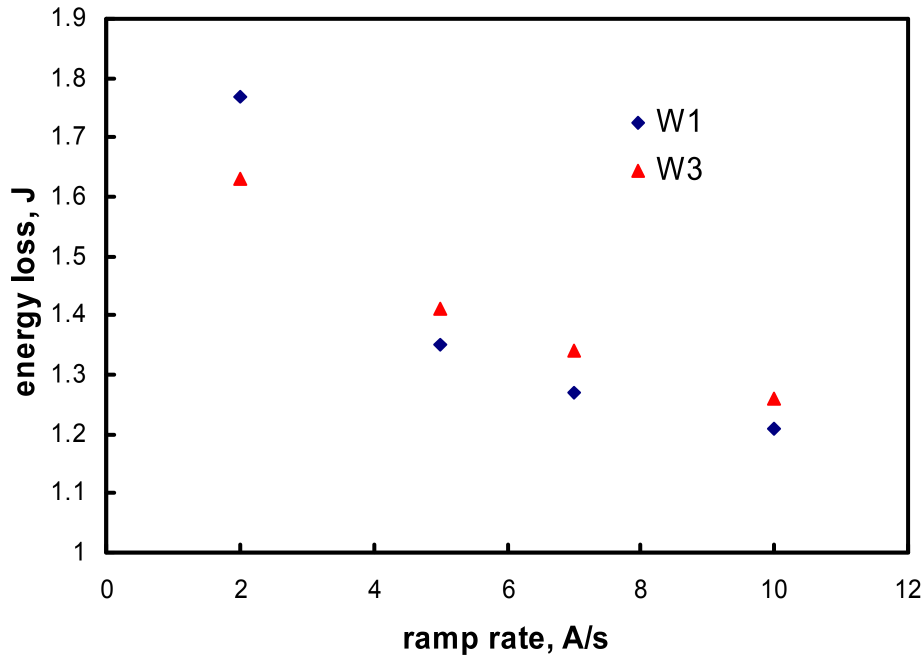

Fig. 10. AC losses as a function of ramp rate

Values of additional energy losses caused by noise are listed in the table below for different ramp rates. All values are obtained by "eieo" program. The conclusion from this table: the more ramp rate the less energy losses both total and caused by noise.

ramp rate, A/s	W tot, J	W noise, J	sigma, J
2	1.77	0.025	240μ
5	1.35	0.019	140μ
7	1.27	0.018	2.3m
10	1.21	0.017	170μ

Table 1. Energy losses (total and caused by noise T=1s) for different ramp rates

In fig. 11 are presented the mean root square deviation (sigma) versus number of ramp profiles response characteristic for different ramp rates. So the sigma value becomes stable from N=5 as in the case without noise.

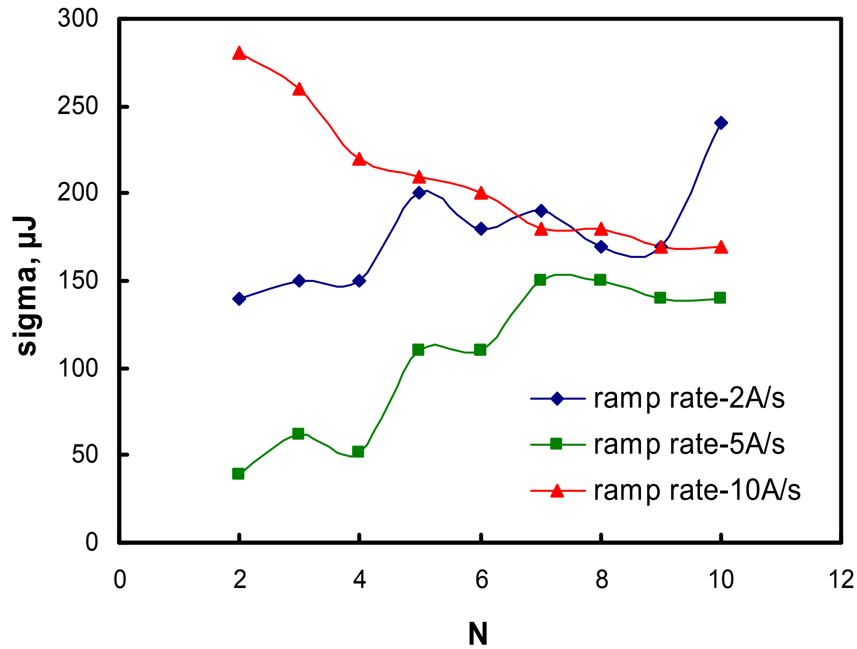

Fig. 11. Mean root square deviation as a function of number of ramp profiles

For another period of noise signal (5s) the plots are the same, so they are simply listed below (fig. 12, 13, table 2).

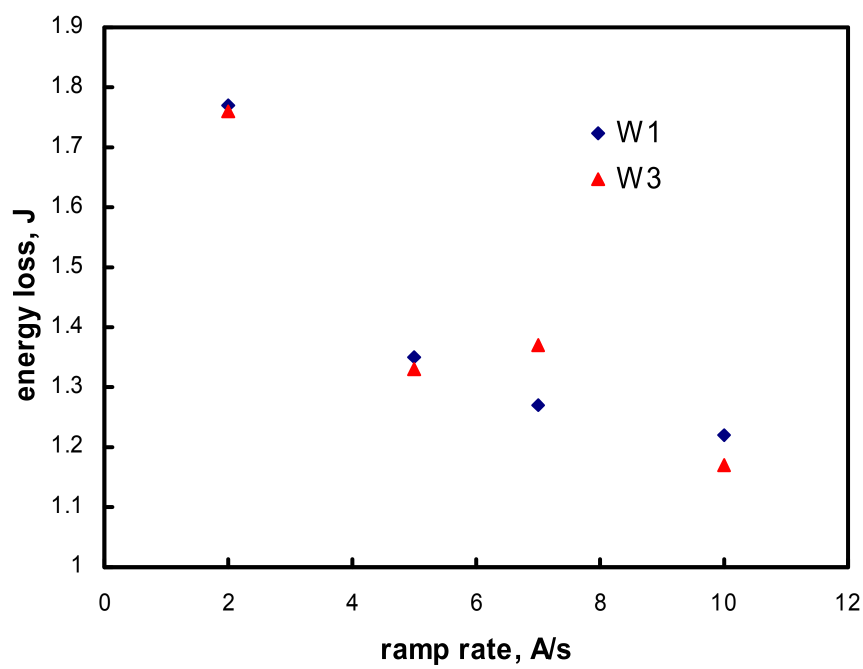

Fig. 12. AC losses as a function of ramp rate

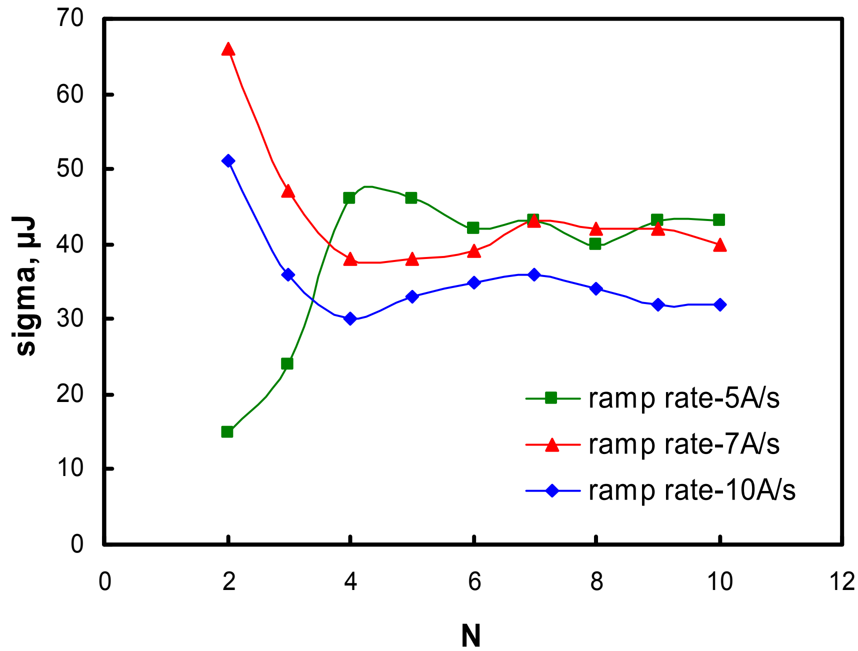

Fig. 13. Mean root square deviation as a function of number of ramp profiles.

ramp rate, A/s	W tot, J	W noise, J	sigma, J
2	1.77	0.025	220µ
5	1.35	0.018	43m
7	1.27	0.018	40m
10	1.22	0.017	32m

Table 2. Energy losses (total and caused by noise T=5s) for different ramp rates.

3) Sampling rate dependence

Values of energy losses can be dependant from the sampling rate. So, for understanding this response the measurements of losses for different sampling rates (0.1, 0.5, 1, 10 ms) with the noise level: T=1 s, A=1 A were performed. The results for different ramp rates are listed in the table 3. The values of energy losses in these experiments are stable for listed ramp rates.

Ramp rate, A/s	Sampling rate, ms	W theory, J	W tot, J	sigma, J
2	0.1	1.63	1.79	350µ
	0.5		1.77	200µ
	1		1.78	450µ
	10		1.78	440µ
5	0.1	1.41	1.36	390µ
	0.5		1.35	110µ
	1		1.35	110µ
	10		1.35	240µ

7	0.1	1.34	1.27	1.3m
	0.5		1.27	1.1m
	1		1.27	1.1m
	10		1.27	1.6m
10	0.1	1.26	1.21	140μ
	0.5		1.21	210μ
	1		1.21	130μ
	10		1.21	120μ

Table 3. Energy losses for different sampling rates.

4) Moving the end point

The real signal always combines with a noise signal in an experiment. For performing a calibration of the program the sinusoidal noise was added to the initial signal. For noise compensation it is necessary to determine the correct integration interval. It should include the whole number of noise periods. The integral $\int_0^{t_{end}} U dt$ with a correct endpoint should be equal to zero. So in the program the function of moving end point was added. Fig. 14 shows the $\int_0^{t_{end}} U dt$ variation with endpoint for calibration experiment (the precise resistance was used instead of a real magnet and a sinusoidal noise was added to the signal). The amplitude and the period of noise are listed in the plot below. So the integration time should be equal to the whole number of noise periods.

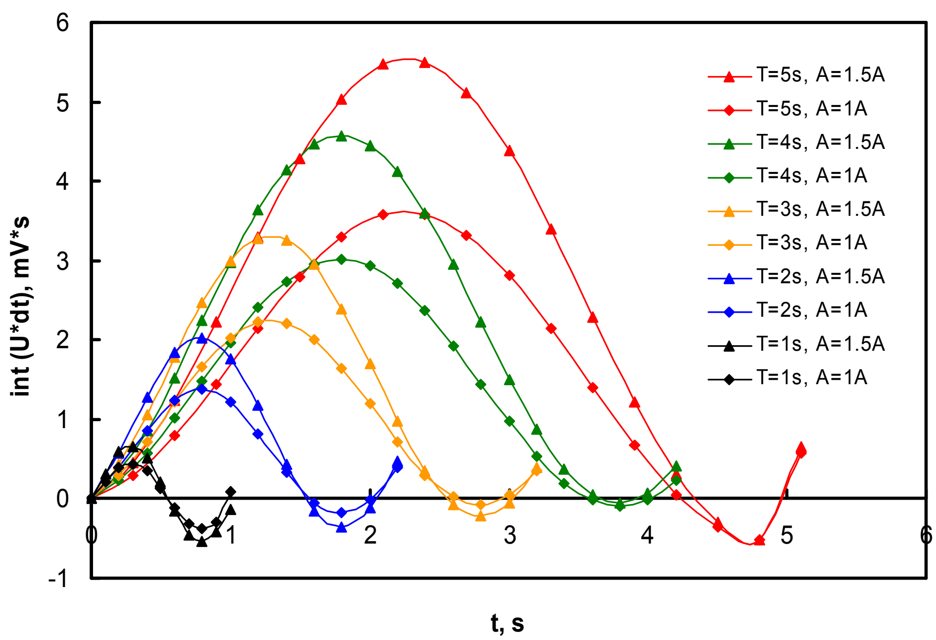

Fig. 14. $\int_0^{t_{end}} U dt$ as a function of noise period

5) TQM-03 energy loss measurements

For doing the experiment with real magnet the KEPCO power supply had been replaced on another one in Vertical Magnet Test Facility (VMTF) for performing experiment [4]. The maximum value of the current during the cycle was 6500 A and the minimum level was 500 A. An experiment with Test Quadrupole Mirror Magnet (TQM-03) for measuring hysteresis and eddy current losses [5] was performed. For different ramp rates (110 A/s, 200 A/s, 250 A/s, 300 A/s) energy losses were calculated. One of the profiles is presented in fig. 15. The signal from DMM 4071 is very noisy. This picture is done for sampling rate 2000 Hz. After that the experiment with sampling rate 60 Hz (fig. 16) had been done. The noise level is much smaller for the sampling rate 60 Hz.

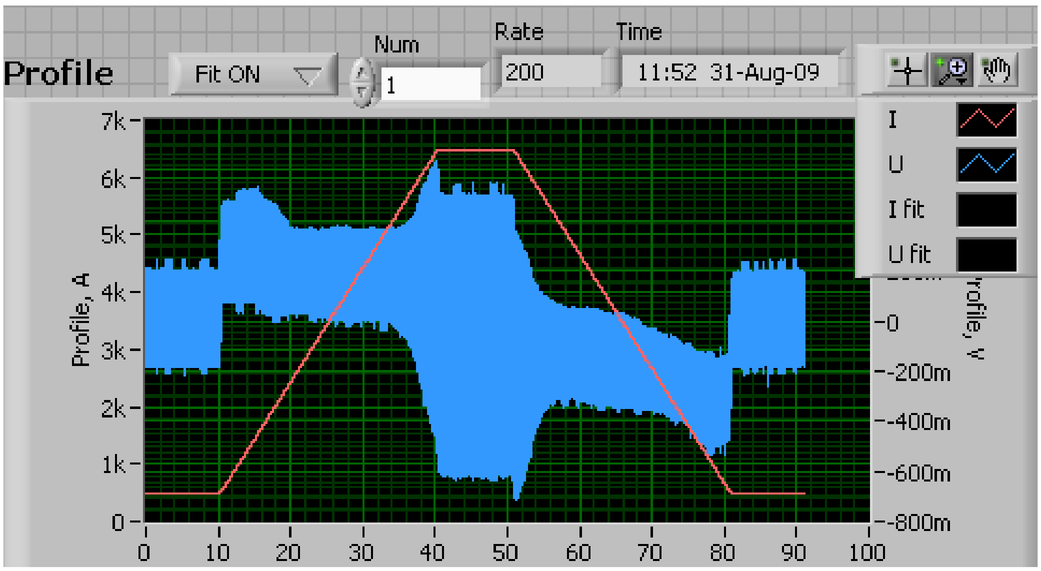

Fig. 15. Profile of signal in TQM-03 (ramp rate 200 A/s, sampling rate 2000 Hz)

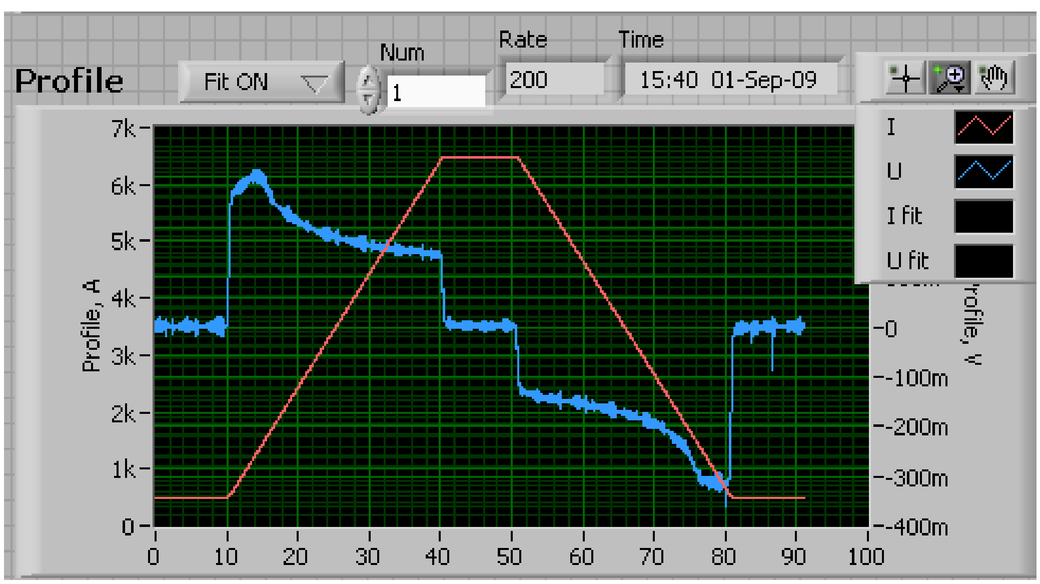

Fig. 16. Profile of signal in TQM-03 (ramp rate 200 A/s, sampling rate 60 Hz)

The results of total energy loss measurements are different for 2000 Hz (for ramp rate 200 A/s – 535±1.7 J) and for 60 Hz (for ramp rate 200 A/s – 499±17 J). Also the data for 2000 Hz sampling rate was taken and the values of current and of voltage were averaged for every 30 points. For doing this procedure program on C++ was written. After that using these modified data the energy loss was calculated (535 J), the same value as for 2000 Hz sampling rate. The form of modified signal is presented in fig. 17. When the sampling rate is increased, the additional losses caused by noise mode of 60 Hz are included. As a result 60 Hz sampling rate is better for correct results. Fourier transformation of the signal didn't give a proper results because a small amount of experimental points.

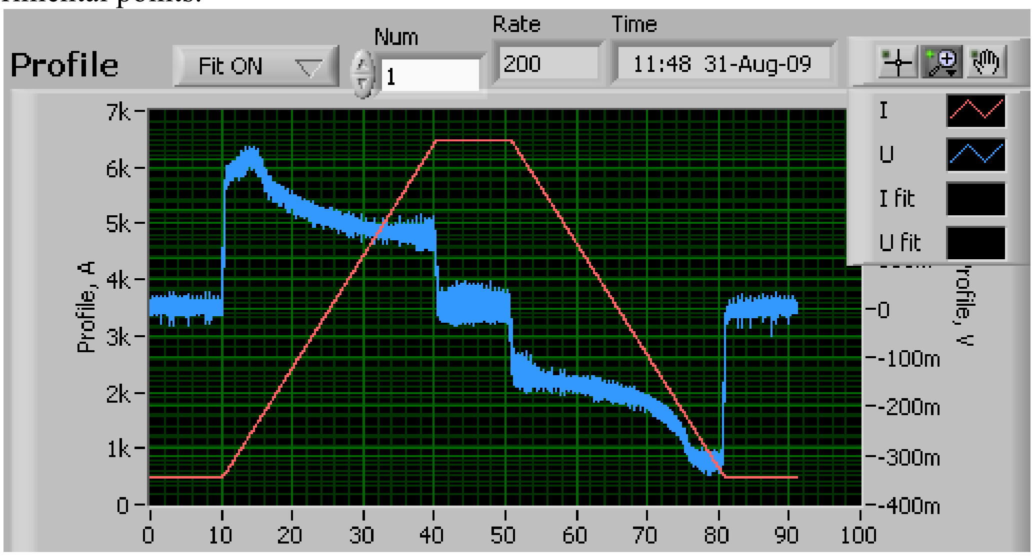

Fig. 17. Profile of signal in TQM-03 (ramp rate 200 A/s, data sampling rate 2000 Hz, after averaging the data)

The results for energy loss measurements were received for sampling rate 2000 Hz and they are presented in fig. 18. For each ramp rate 5 profiles were obtained for measuring the mean root square deviation for statistics. After linear approximation of this data the value of hysteresis loss was determined, it is 406±5.3 J and the value of eddy current loss is 632±24 mJ/(A/s) according to the equation (4).

$$W = (Ecl) \cdot (R/r) + (Hl) \qquad (4)$$

where W – total value of energy losses, Ecl – eddy current losses, R/r – ramp rate, Hl – hysteresis loss.

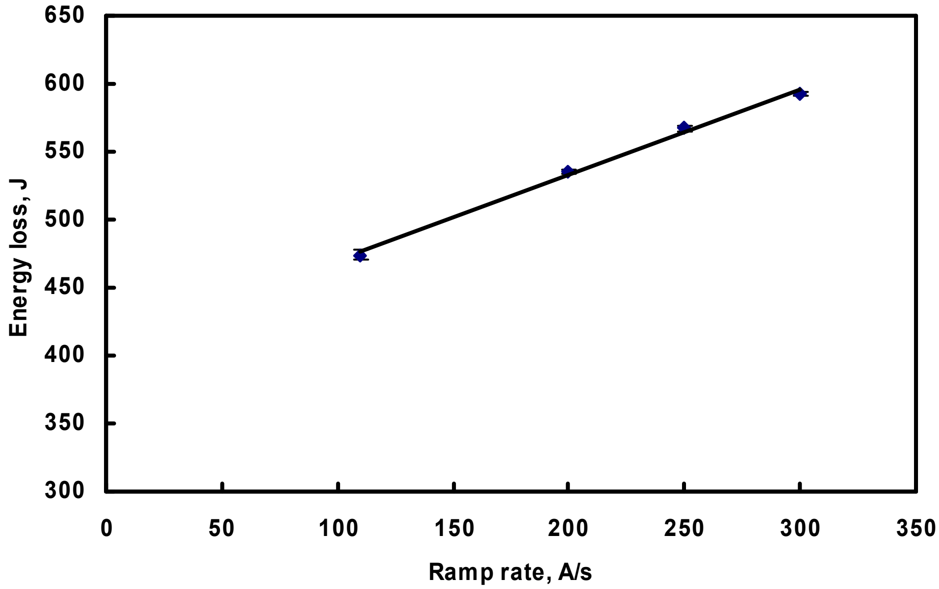

Fig. 18. Energy losses in TQM-03

Also a series of experiments were performed in which the end point of integration was moved, the goal was to minimize the value of integral $\int_0^{t_{end}} U dt$ (Uint). The results for 2000 Hz sampling rate are presented in table 4 where W is the energy loss with maximum available time of integration, W_move is the energy loss after moving the end point. According to these results the minimum level of $\int_0^{t_{end}} U dt$ is achieved for maximum integration time and moving the end points is useless. It can be explained by decaying of persistent current at the end of ramp cycle. According to theoretical predictions this decaying time for this type of magnet is about 50 s.

Ramp rate, A/s	W, J	W_move, J	sigma, J	Uint, mV	Uint_move, mV
110	474	474	3.4	3.44	3.44
200	535	535	1.7	2.92	2.92
250	567	567	1.9	4.26	4.26
300	593	593	1.8	3.94	3.94

Table 4. Energy losses in SC magnet

Conclusions

In present paper the value of energy losses for Test Quadrupole Mirror Magnet (TQM-03) was determined for temperature of the magnet 4.2 K. The maximum value of the current during the heating cycle was 6500 A and the minimum level was 500 A. For different ramp rates (110 A/s, 200 A/s, 250 A/s, 300 A/s) energy losses were calculated. The value of hysteresis loss is 406±5.3 J and the value of eddy current loss is 632±24 mJ/(A/s). The dependence energy losses verse sampling rate was found out. An assumption that correct results (without inclusion energy losses due to the noise) can be received with 60 Hz sampling rate was made.

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